Spatial and Temporal Relationships of Old-Growth and Secondary Forests in Indiana, USA

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ABSTRACT: We examined the spatial pattern of forests in Indiana to (1) determine the extent, connectivity and percent edge of all forests; (2) examine the change in connectivity among these forests if all riparian zones were replanted to forest or other native vegetation; (3) determine the location, spatial dispersion, and percent edge of current old-growth forest remnants; (4) predict future changes in area and spatial distribution of old-growth forests based on current land management plans of public agencies; and (5) discuss biological implications of different edge widths, patch sixes, and spatial configurations of forests in Indiana. To achieve this, we produced a map of forested riparian zones using a Geographic Information System (GIS) buffering function and developed GIS models to predict locations of potential old-growth forests on lands designated in public agency management plans as preserves or unmanaged forests. A proximity index (PX) was used as a quantitative measure of effective connectivity of forest patches. PX values ranged from 0 to nearly 3,000, where a value of 0 is effectively isolated and a value of 3,000 is very well connected. For the 9,508 patches and 2,026,716 ha of all forests in both Indiana and the surrounding area, the average PX was 19.49. Adding a 200-m forest buffer to both sides of all nonforested riparian areas resulted in a decreased number of fragments to 3,634 and an increase of 1,724,664 ha of forest (the buffer). A 20-m buffer would add 172,466 ha of forest. The PX was not used to analyze riparian areas because it was not appropriate for the dendritic pattern formed when riparian areas were revegetated. Total area of old-growth forests ≥ 4 ha held in public trust in Indiana is 362 ha divided among 19 forests. An additional 8 sites ≥ 4 ha in private ownership contain 215 ha. Most old-growth forests are isolated within an agricultural matrix. The percentage of old-growth forest areas located within 40 m, 200 m, 400 m, and 600 m of a nonforest edge were 23%, 75%, 89% and 93% respectively. PX values for all 19 old-growth sites were 0, implying that they are very isolated sites. If current public forest management plans are followed, the area and number of old-growth forests will increase and their relative isolation will decrease. Potential future old-growth forests consisted of 137 patches and 82,520 ha with an average PX of 1.8. Of this amount 27,297 ha were within Hoosier National Forest purchase boundaries but are currently in private ownership.

Index terms: connectivity, forest edge, Indiana, old-growth forest, proximity index

INTRODUCTION

In 18 16, Indiana's landscape was approximately 87% forested (Petty and Jackson 1966). However, it is unknown how much forest was old growth at that time. Fire was used by Native Americans for agricultural clearing and driving game (DenUyl 1954, Campbell 1989, DeVivo 1990, Reich et al. 1990, Denevan 1992). This use of fire probably changed the landscape. Military raids on Native American villages in Indiana burned adjacent cornfields (Latta 1938). When these native peoples moved, forests regenerated on their abandoned agricultural and village sites. European settlement resulted in additional forests being removed for agricultural purposes, with remaining forests existing in a fragmented landscape (Parker 1989). In 1986, Indiana's forest vegetation was estimated to be 19.3% (I.78 million ha) of total land area (Smith and Golitz 1988).

Today, Indiana's old-growth forests (as defined in "Methods") are known to exist at 33 sites comprising approximately 607 ha (Parker 1989); most occur within an agricultural matrix. Other forest sites have been set aside as preserves throughout the state in state forest, state and county parks, Hoosier National Forest, and fish and wildlife properties; by universities; and as state nature preserves as well as other public land trusts. Although protected, these sites are not old-growth forests at the present time. Spatial relationships such as isolation or connectivity of today's old-growth

forests or of the set-aside forest sites have not been examined at the landscape scale.

The importance of connectivity of habitat patches to movement of selected vertebrates (birds, mammals and a frog) has been noted (MacClintock et al. 1977, Middleton and Merriam 1981, Forman and Gordon 1984, Merriam 1984, Fahrig and Merriam 1985, Henderson et al. 1985, Polla and Barrett 1993, Gulve 1994). Other spatial characteristics such as edge also have ecological consequences.

Edge effects differ for plants and animals. Estimates of the distance into a forest over which plant edge effects occur vary depending on attributes measured. However, most estimates for plant edge effects fall within 40 m inward from an edge (Gysel 195 1, Wales 1972, Purse11 and Parker 1988, Brothers and Spingam 1992, Brothers 1993). As an example for animals, edge is ecologically important to ground-nesting birds (Brittingham and Temple 1983, Wilcove et al. 1986, Andrèn and Angelstam 1988, Noss 1991, Hoover and Brittingham 1993, Robinson et al. 1995). This edge can extend 600 m or more into a forest. Paton (1994) found that most conclusive studies imply that edge effects for avian nest success take place within 50 m of an edge. However, he suggested that this conclusion be interpreted cautiously because of differences in experimental design among the studies. In our study we examined edge, connectivity, and future changes in old-growth forests across the Indiana landscape. By understanding present conditions through these measures we can make more informed decisions about future research and management needs.

The objective of this study was to examine the spatial pattern of forests in Indiana to (1) determine the extent, connectivity, and percent edge of all forests; (2) examine the potential change in connectivity among these forests if all riparian zones were replanted to forest or other native vegetation; (3) determine the location, spatial dispersion, and percent edge of current old-growth forest remnants; (4) predict future changes in area and spatial distribution of old-growth forests based on current land management plans of public agencies; and (5) discuss biological implications of different edge widths, patch sizes, and spatial configurations of forests in Indiana.

METHODS

Definitions

We defined old-growth forests in Indiana as those forests with overstory canopy trees > 150 years old, little human-caused understory disturbance during the past 80 to 100 years, all-aged structure, multilayered canopies with dominant canopy trees from 80 to 160 cm dbh and understories of late-seral shade tolerant trees. We also looked for a mosaic of all-aged canopy gaps and significant numbers of standing and downed dead trees (Parker 1989). Potential old-growth forests were defined as those forests not presently in an old-growth condition, but which have been set aside as preserves throughout Indiana. Potential old-growth forests are expected to develop old-growth characteristics in time.

Location of Sites

To locate existing and potential old-growth forests we used literature searches, questionnaires sent to district foresters, surveys sent to all public land-holding agencies, and interviews with public land-holding agency personnel. To confirm sites that were questionable, we made on-site visits. The surveys included questions concerning the location and attributes for all forest preserves that will eventually develop old-growth characteristics. Because our GIS data had a 4-ha resolution, only sites ≥ 4 ha were included in spatial analyses. Eight privately owned old-growth sites ≥ 4 ha in extent, totaling 215 ha, had no designated plans to maintain them as old-growth sites. Owing to their uncertain future, these sites were not included in the analysis to predict future matrices. However these sites were used to examine connectivity among current old-growth sites. Sites not included because they were < 4 ha in extent were seven old-growth sites—six in public trusts and one privately owned.

GIS Data and Analysis

To describe Indiana's current forest cover, we used U.S. Geological Survey (USGS) land use/land cover data at a 1:250,000 scale and 200 x 200 m resolution. Forests adjacent to the political boundaries of Indiana were included in this analysis because land managers are encouraged to take a landscape perspective in land use planning (Vankat et al. 1990, Probst and Crow 1991, Oliver 1992, Diaz and Apostol 1993, Hann et al. 1994). By producing a map showing forest connectivity beyond political boundaries we provide a useful example of forest patch analysis from this landscape perspective. Total forested area for Indiana covered 1,55 1,823 ha. An additional 474,893 ha of forest were outside but within a maximum of 75 km of Indiana borders. For these areas outside Indiana, we used all of the data available to us in order to achieve maximum coverage. To delineate riparian zones, USGS digital line graphs (DLG) data at a scale of 1:100,000 were used. The DLG vector data were converted to data organized in rows and columns (raster format) at a 200 x 200 m resolution, and a GIS buffering function was used to create a map of vegetated riparian zones. The buffering function was used to designate an area of a specified width around the riparian zones. Because of the restriction of the 200-m resolution, vegetated riparian zones were 200 m on each side of streams and rivers and 200 m around lakes. The map of all forests was combined with the riparian zone map using GRASS 4.1 GIS software (U.S. Army CERL, Champaign, Illinois) to model forests connected by vegetated riparian areas. No riparian data were available for the easternmost edge of central Indiana or for two areas outside Indiana—southeast and southwest-so the forested riparian corridor model does not include these areas.

We mapped all existing and potential old-growth sites on 7.5-minute quadrangle maps and digitized them. UNIX ERDAS 7.5 (ERDAS Inc., Atlanta, GA, 01991) was used to grid the old-growth and future old-growth sites at a 200 x 200 m resolution to estimate edge areas potentially important to bird nesting success and a 40 x

40 m resolution to estimate edge areas important to vegetation. Because data for Hoosier National Forest (HNF) came in a raster format at a 200-m resolution, we could not obtain 40-m edge estimates. However, we used regression analysis to predict the percent area in edge for HNF for a 40-m edge. The regression was established between percent area in edge and edge width for the edge widths of 200 m, 400 m, and 600 m. The regression (R^2 = .99, P-value = 0.06) was: Y = 18.33 + 0.0725x, where Y = % of forest in edge and x = distance from edge in meters.

We identified individual forest patches using a clumping function that groups cells that form physically discrete forests and then assigns a unique identification number to each forest patch. A proximity function was used to identify edge and core areas. ERDAS IMAGINE 8.1 (ERDAS Inc., Atlanta, Georgia, 01994) was used to identify individual forests and annotate maps. Edge was defined as the forest/nonforest interface-. At a 200-m resolution forest edges show up as more convoluted than at a 500-m resolution. Gleick (1987: 95-96) explained the advantages and disadvantages of scale in his discussion of fractal dimension, noting that edge patterns at one resolution tend to repeat themselves at another resolution. Scale is a basic concern to anyone planning landscape scale spatial analysis.

We chose the 200-m resolution data for all but one analysis because these were the most detailed data available for all coverage, and this was the smallest resolution that could be practically used with the Habitat Island Spatial Analysis (HISA) program and existing hardware. The one analysis not done at the 200-m resolution dealt with edge. Because we digitized the old-growth forest and future old-growth forest data from 7.5minute quadrangle maps, we were able to determine edge characteristics at a 40-m resolution for old-growth forests, both current and potential.

We used two models of a potential old-growth landscape. The first model, MPU (Model-Public), included all publicly owned lands currently set aside (likely to develop old-growth characteristics). The second model, MPR (Model-Private), included these areas plus sites designated by the 1991 Hoosier National Forest (HNF) plan as unmanaged areas within their purchase boundaries that are currently in private ownership. Since 1940, the average purchase area of private lands for HNF has been 1,159 ha year^{-1}, but this has declined in recent years. The HNF forest sites included in both MPU and MPR are areas where the 199 1 plan emphasizes protection to create extensive areas of older forest.

We used the HISA program (Gustafson and Parker 1992) to calculate a proximity index (PX) (Figure 1) and to produce a proximity map of forest patches across the Indiana landscape. PX is used to quantify the spatial context of a habitat patch in relation to its neighbors. In this study, it was used as a quantitative measure of effective connectivity of forest patches across a large landscape. The theory of the PX value is based on island biogeography where large PX values represent large forest patches close together and small PX values represent small, widely distributed forest patches. The PX analyzes the landscape context of these patches at a specific search distance (proximity buffer). In this analysis the PX value was used as an indicator of the connective character of the landscape. Using a search buffer of a particular size (see proximity buffer, Figure 1), we modeled how fragmentation of the landscape might be perceived by an organism at that scale, by illustrating the effective connectivity in map form (Gustafson and Parker 1994). To keep spatial indices comparable among analyses we calculated PX with an arbitrary search distance of 600 m in all cases.

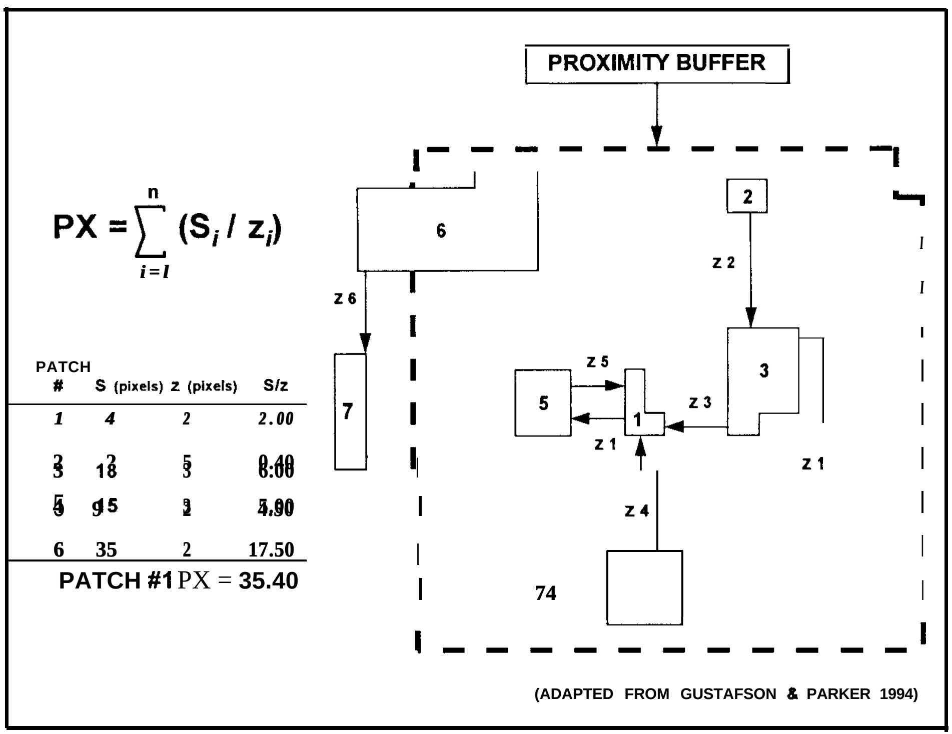

Figure 1. Illustration of the calculation of a proximity index (PX). A PX value was calculated for each forest patch by Identifying each forest patch i whose edge lies at least partially within a specified number of pixels (proximity buffer) of the patch belng Indexed. The proxlmlty buffer for patch 1 is shown as the dashed line In this figure. In this study we used 3 pixels (600 m) as our proximity buffer. PX is calculated using area (S_i) and the edge-to-edge distance (z_i) from patch i to Its nearest-neighbor forest patch of each of the n forest patches identified wlthln the buffer, including the patch being Indexed (Gustafson and Parker 1994). If there Is no other patch wlthln the proxlmlty buffer, then z_i equals zero. High PX values represent large forest patches, close together and low PX values represent small isolated forest patches.

RESULTS

Extent and Connectivity of All Forests

Total area in this study was 13,104,912 ha within all or part of thirty-six 30 X 60 minute series USGS maps. These maps were Adrian, Elkhart, South Bend, Chicago, Kankakee, Knox, Fort Wayne, Defiance, Watseka, Logansport, Wabash, Lima, Danville, LaFayette, Muncie, Piqua, Paris, Indianapolis, New Castle, Dayton, Terre Haute, Bloomington, Greensburg, Cincinnati, Olney, Vincennes, Bedford, Madison, Falmouth, Mount Vernon, Princeton, Jasper, Louisville, West Frankfort, Evansville, and Tell City. The study area was limited to UTM coordinates in the northwest comer of X = 390,000, Y = 4,635,388 and in the southeast comer of X = 700,000, Y = 4,175,388.

All forests in Indiana and surrounding areas as defined above consisted of 2,026,7 16 ha divided among 9,508 forest patches with an average PX value of 19.5 (Table 1). Patches created by the dissection of forests by narrow roads were not recognized in these models owing to the 200-m resolution and the insensitivity of the PX to such road barriers. The PX map (Figure 2) shows proximity values and the associated hectares in each PX range. The average forest patch size is 2 13 ha. Most forest patches were very isolated, having a PX falling in the category IO.5 (yellow color in Figure 2 and mostly small patches in Figure 3). It is unlikely that forest organisms with a 600-m dispersal distance would be able to maintain a viable population in this area. The maximum PX value was 2,839.3. The largest single forested patch, 225,860 ha in extent, occurs in central, southwestern Indiana with a PX value of 2,227.9. With such a high PX value this area and the surrounding forest patches should be very permeable to a forest organism with a 600-m dispersal distance. In Figure 2 this area shows up as most of the color associated with the PX of 2,000–3,000. The second largest patch is 189,912 ha in extent with a PX of 1,673.7 comprising most of the color associated with the PX range of l,OOO-2,000 (Figure 2).

Edge of All Forests

The area of forest within these patches that qualifies as edge depends on how "edge" is defined. For example, 60% of the total forest area in Indiana and surrounding area is in edge for a 200-m edge, 79% is in edge for a 400-m edge, and 87% is in edge for a 600-m edge (Figure 4). The Indiana landscape is dominated by an agricultural matrix that has resulted in linear forest edge characteristics, making analysis at the 200-m resolution more useful than if edges were more convoluted. However, for landscapes with more convoluted edges and small inclusions, a higher resolution would increase our ability to identify more detailed features such as agricultural fields < 4 ha in extent that are within forests, more intricate edge features, riparian area vegetation < 200 m wide, and forest patches < 4 ha.

Riparian Corridors

Adding corridors can increase dispersal (Polla and Barrett 1993) and help to maximize biotic diversity (MacClintock et al. 1977) of forest fragments. In Indiana these corridors could be forest in originally forested areas or other native vegetation such as prairie in areas where prairie was once the dominant native vegetation. With the addition of a 200-m forest buffer around all nonforested riparian areas, the number of all forest patches would decrease by 62% and the total forest area would increase by 85%. The largest patch created in this scenario is 3,574,300 ha in extent. A 200-m forested riparian buffer would result in a 1,724,664 ha increase in forest in areas presently nonforested. A 50-m buffer would increase forest or other native vegetation by 2 1 %, and a 20-m buffer would result in a 9% increase. However we were not able to evaluate the change in connectivity of 972 patches (10% of all forest patches) totaling 17 1,676 ha in three areas (Figure 4, boxed areas) owing to lack of riparian data. After reviewing to-

Table 1. Summary of five landscapes in Indiana. Values are for forests within Indiana political boundaries, unless otherwise noted.

Forest Landscape	Total Area (ha)	Number of Forest Fragments	Largest Forest Fragment	Average PX	Largest PX
All forests [a]	2,026,716	9,508	225,860	19.5	2839.3
All forests plus vegetated riparian zones [ab]	3,751,380	3,634	3,574,300	**	**
All forests plus vegetated riparian zones [b]	2,890,608	2,599	2,629,444	**	**
Potential old-growth forest in public ownership (Model MPU)	55,223	216	14,968	3.9	81.5
Potential old-growth forest in public and private ownership (Model MPR)	82,520	137	20,568	1.8	110.0

[a] Includes forest outside Indiana political boundaries

[b] Total area, number and largest forest fragment based on a 200-m-wide vegetation buffer around all non-forested riparian zones.

** PX analysis not appropriate for this dendritic pattern. PX was developed to evaluate forest patches in an agricultural landscape, pographic maps covering these 972 forest patches, we believe that these areas would have shown similar increased **connec-**tivity.

Old-Growth Forest Edge

In the study area, there are 19 old-growth sites $\geq$ 4 ha in extent held in public trust (Table 2) totaling 362 ha. The hugest **pub-lic** trust site is the **76.9-ha** Wesselman Woods Nature Preserve in southern Indiana (Vanderburgh County). Mean percent area of all old-growth sites in edge averages 45% of the total area when edge is defined

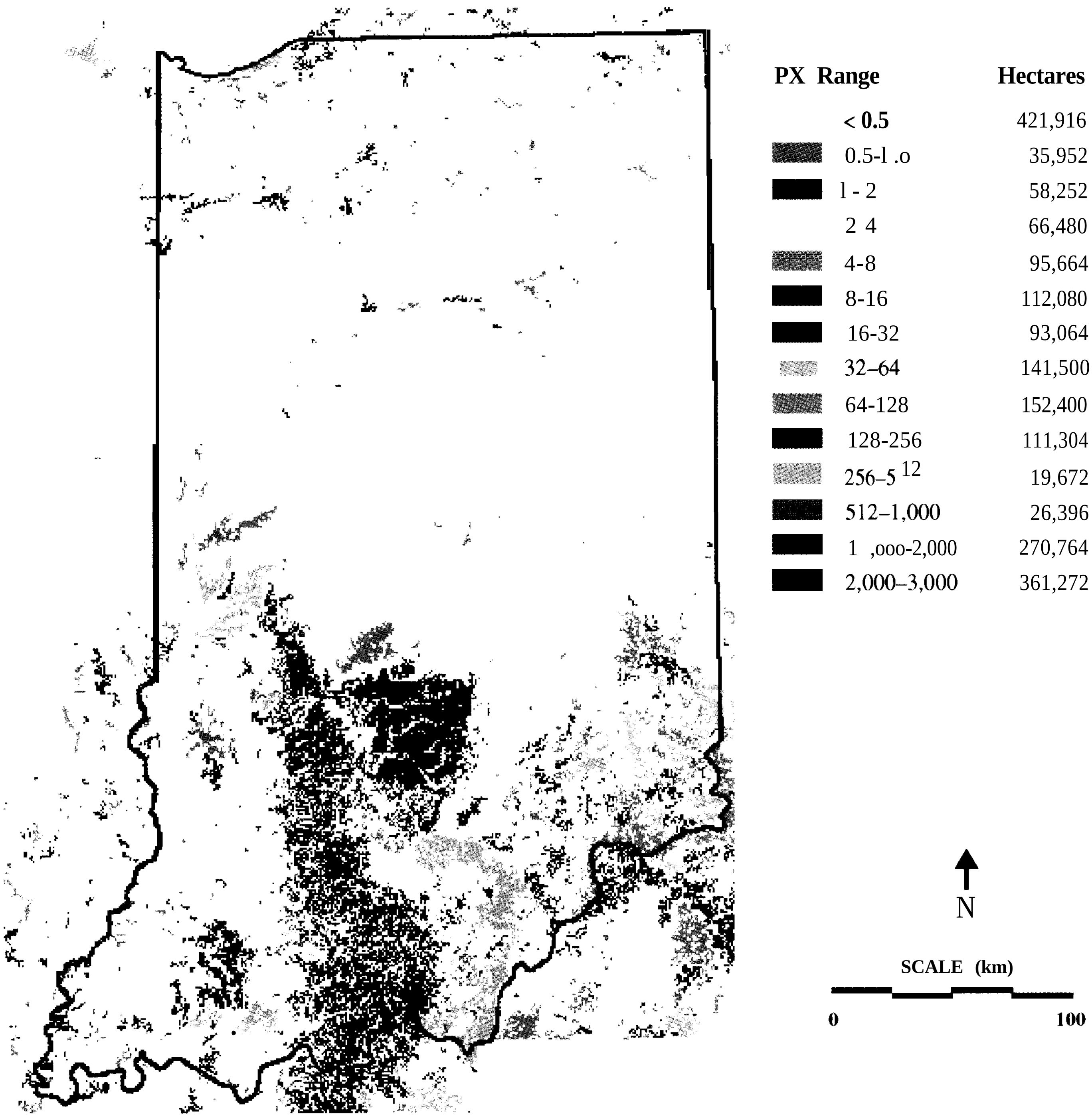

Figure 2. Proximity map of **all** forests In **Indiana** and surrounding area. There are **9,508** forest patches and **2,026,716** ha of forest. The northern half of the state **is** relatively fiat, with a high agricultural/forest area ratio. South-central Indiana shows the largest areas of forest and has much more vadable topography. The southern third of the state is bordered by the Wabash **River** (west) and the Ohio River (south). A 600-m **proximity** buffer was used. Note: we did not have land **use/land** cover data outside of Indiana for the southeast corner.

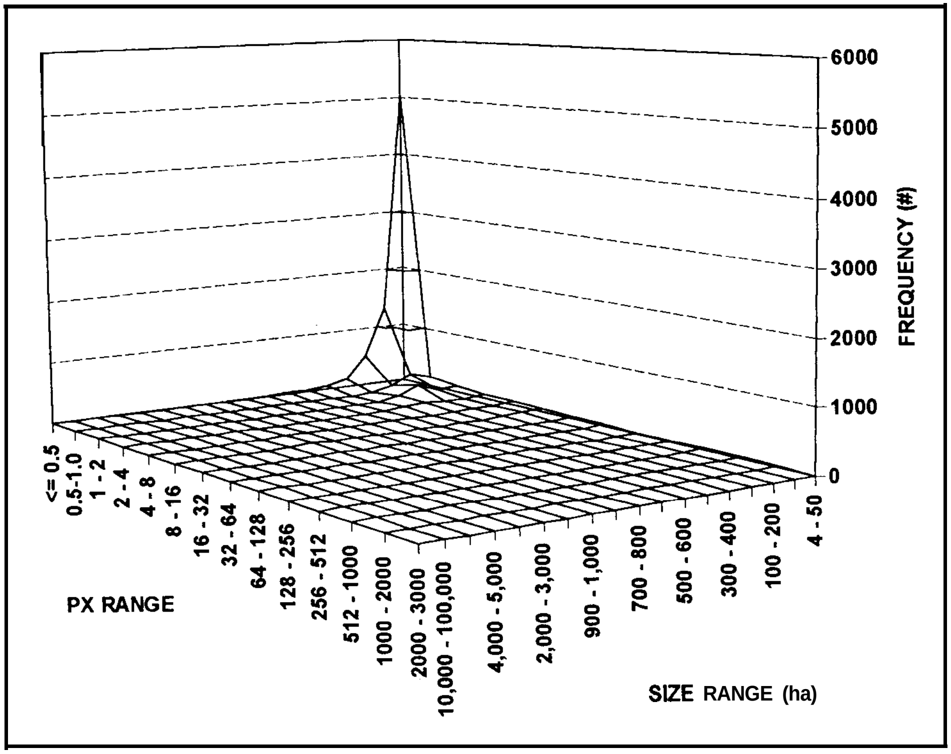

Figure 3. Number of forest patches (frequency) that fall within each PX range and size range combination for the scene in Figure 2. The highest frequencies are associated with the smallest forest patches. These patches also have the lowest PX values, meaning that they are the most Isolated patches In this landscape.

to be 40 m inward from where the old-growth forest and any non-old-growth area meet, whether younger forest or nonforest, 99% for a 200-m edge, and 100% for 400-m and 600-m edges (Table 3). When viewed within the context of the surrounding landscape of secondary forest, the average percent edge for the 19 old-growth sites for edge widths of 40 m, 200 m, 400 m, and 600 m decreases to 23%, 75%, 892, and 93% respectively. Based on these results, if surrounding forests were converted to non-forest uses, the percentage in edge of the old-growth sites would increase. Over time, increased edge might increase the invasion of alien plant species in these edges (Brothers and Spingarn 1992).

Old-Growth PX and Nearest Neighbor Distances

The proximity index of all old-growth forest patches based on their proximity to each other was 0. For such a small number of very isolated patches it is also useful to include a more direct measure of the magnitude of isolation, such as the nearest neighbor distance (NND). Average NND among old-growth forests was 35,850 m (Table 2). When considered as part of the surrounding landscape of all forests, average PX of old-growth patches = 189.4 and average NND = 844 m for the 19 old-growth sites. Although the average PX value was larger than in the old-growth landscape, there was considerable variation with a standard deviation of 454.2 and a range from 0 to 1,673.7.

There were three sites with very large PX values, but most values were low. The largest PX value was 1,673.7 at Scout Ridge Nature Preserve located in Morgan-Monroe State Forest. The second largest PX value was 1,13 1.4 for Pioneer Mothers Memorial Forest located in Hoosier National Forest. Hoot Woods had the third largest PX value at 718.5 (Table 2) and exists in a landscape of privately owned forest lands. Eleven of the 19 sites had PX values of 0, even within the landscape of all forests.

There are eight privately owned old-growth sites ≥ 4 ha in extent totaling 215 ha. If the eight privately owned sites are combined with the 19 sites in public trusts, both the average and largest PX for all sites is still 0. When considered spatially in relation to only other old-growth forests, each old-growth site is very isolated. Average size of old-growth sites is 19.1 ha for the 19 public trust sites; 21.4 ha when the 8 privately owned sites are also included.

Old-Growth Forest Combined with Potential Old-Growth Forest

The spatial isolation among the current 19 public trust old-growth sites remained, even when old-growth was augmented by the potential old-growth forests. The "potential old-growth forests" added old-growth forest either as the publicly owned set aside forests (model MPU) or the public plus privately owned set aside forests (model MPR). With the addition of potential old-growth sites, because these sites are distributed throughout the state, the distance between sites decreases. Current old-growth sites are closer to potential old-growth sites than to other current old-growth sites. Average nearest neighbor distance (NND) was 35,850 m for the 19 old-growth sites but decreased to 13,447 in model MPR and 13,476 m in model MPU (Table 2). There is little change in NND between model MPU and model MPR when considering only the current 19 old-growth forests within the landscape of potential old growth. The main reason for this is that model MPR adds potential old-growth forests only to the HNF, making the addition of forest in model MPR a localized phenomenon.

Potential Old-Growth Forest

For all potential old-growth forests, there were major differences between the two models. For model MPU, which considered all publicly owned lands, the mean PX = 3.9, mean NND = 5,603 m, and total area was 55,223 ha for all 216 sites. Model MPR, which also included privately owned lands within the HNF purchase boundaries, had a mean PX = 1.8, mean NND = 8,023, and total area of 82,520 ha for all 137 sites. Even though more area

Table 2. Public trust old-growth sites and metrics by type of forest landscape, for Indiana. Model MPR is a forest landscape of potential old-growth forest that includes sites within the purchase boundaries of the Hoosier National Forest that are currently in private ownership. Approximately 1,159 ha $year^{-1}$ of private land has been purchased for the Hoosier National Forest since 1940. Model MPU includes only potential old-growth forests that are currently in public ownership.

Old-Growth Site ID and Location			Type of Forest Landscape With Which Old-Growth Forests Were Combined: Present Day Old-Growth ≥ 4ha		All Forests in Indiana		Future Old-G W/ Private HNF (Model MPR)		Future Old-G Public Ownership (Model MPU)	
Name Of Site	County	Size (ha)	PX	NND	PX	NND	PX	NND	PX	NND
Bendix Woods N.P.	St. Joseph	10.9	0.0	22,632	0.0	632	0.0	16,901	0.0	16,901
Eunice H. Bryan N.P.	Clinton	11.7	0.0	39,041	0.0	4,020	0.0	19,502	0.0	19,502
Calvert and Porter Woods N.P.	Montgomery	16.2	0.0	39,041	0.0	3,945	0.0	23.125	0.0	23,125
Davis-Purdue Research Forest	Randolph	20.6	0.0	58,566	0.0	1,217	0.0	29,259	0.0	29,259
Donaldson Woods N.P.	Lawrence	27.1	0.0	20,321	5.8	200	0.0	13,640	0.0	13,640
Hemmer Woods N.P.	Gibson	26.3	0.0	28,288	0.0	849	0.0	28,288	0.0	28,288
Hoot Woods	Owen	33.2	0.0	42,325	718.5	200	0.0	11,588	0.0	11,588
Kieweg Woods	Vigo	17.4	0.0	56,604	5.8	200	0.0	14,311	0.0	14.311
Kingsbury Black Oak Woods	Laport	16.2	0.0	22,632	0.0	400	0.0	15,832	0.0	15,832
Laughery Bluff N.P.	Ripley	15.0	0.0	8,376	57.5	200	0.0	1,400	0.0	1,400
Lubbe Woods N.P.	Dearborn	13.8	0.0	8,376	0.0	447	0.0	8,210	0.0	8,099
McNabb-Walter N.P.	Allen	7.7	0.0	113,477	0.0	1,000	0.0	17,862	0.0	17,862
Pioneer Mothers Memorial Forest	Grange	15.0	0.0	20.321	1,131.4	283	0.0	3,499	0.0	4.162
Scout Ridge N.P.	Monroe	6.1	0.0	42,325	1,673.7	200	0.0	1,811	0.0	1,811
Shrader-Weaver N.P.	Fayette	11.3	0.0	58,566	0.0	600	0.0	24,154	0.0	24.154
Tribbett Woods	Jennings	13.4	0.0	6,551	1.1	200	0.0	6,551	0.0	6,551
Wells Woods N.P.	Jennings	8.1	0.0	6.55 1	0.0	447	0.0	6,551	0.0	6,551
Wesselman Woods N.P.	Vanderburgh	76.9	0.0	28,288	0.0	800	0.0	5,604	0.0	5,604
Woolen's Garden N.P.	Marion	15.4	0.0	58,873	5.6	200	0.0	7,400	0.0	7,400
Mean Values		**19.1**	**0.0**	**35,850**	**189.4**	**844**	**0.0**	**13,447**	**0.0**	**13,476**
Standard Deviation of Population		**15.2**	**0.0**	**25,439**	**454.2**	**1,117**	**0.0**	**8,450**	**0.0**	**8,414**

N.P. = Nature Preserve
PX = Proximity Index
NND = Nearest Neighbor Distance (m)
Private HNF = Areas designated in the Hoosier National Forest Plan as set-aside areas within future purchase boundaries that are presently in private ownership.

was added in MPR, PX was less than in MPU owing to the isolation of large sites (Figure 5). In MPR, 32% of the forested area is in edge for a 200-m edge, 49% for a 400-m edge, and 6 1% for a 600-m edge.

The total area of potential old-growth forest within the HNF purchase boundaries is 67,401 ha, of which only 40,104 ha is currently in public ownership. The size of the HNF forests makes these lands potentially the most important future old-growth lands in the state. For instance, they could be important breeding sites for source populations such as neotropical migratory birds. However, the old-growth forest is not necessary for their survival. A younger forest may be just as acceptable.

Amount of forest in edge, for a 40-m edge for all potential old-growth sites, excluding the HNF forests, was 24%. For a 40-m edge, the estimated percent area of all potential old-growth forest (including HNF) within 40 m from that edge is 21%. This is considered a rough estimate from the regression technique because it extrapolates beyond the resolution of the data (200 m) and assumes a linear relationship. The 21% edge estimate for areas including HNF is less than the 24% for areas that exclude the HNF forests as expected, owing to the larger potential old-growth areas in HNF.

DISCUSSION

Forests across Indiana and forests beyond its political borders were found to be distributed mostly in small patches with little connectivity. For all forests, the largest PX values were located in south central Indiana, indicating that this area might be perceived as less fragmented by an organism with a 600-m dispersal distance, the distance used to calculate PX in our study (Figure 2).

Recommendations for Managers

With reduced budgets, public land-holding agencies will need to reduce expenditures on land acquisitions and other projects. Such agencies could use a PX map in their decision-making process to help identify high priority areas for acquisition or revegetation. For example, the PX has been successfully used to interpret habitat quality (Gustafson et al. 1994). By focusing on areas that require relatively small expenditures to increase habitat connectivity or quality, public funds could be used most effectively.

Edge of All Forests

Based on existing literature, the potential impact of the current fragmented character of Indiana forests on different species depends on the species of interest. Plant edge effects were estimated to take place within 40 m of the edge (Gyse1195 1, Wales 1972, Purse11 and Parker 1988, Brothers and Spingam 1992, Brothers 1993). Because the resolution of the forest data was 200 m, edge effects less than 200 m were not estimated for all forests. However, we were able to digitize the old-growth and potential old-growth sites to allow us to estimate a 40-m edge. The 40-m edge was 21% to 24% for these forests and is likely to be near this range for all forests.

There is considerable variation in the literature regarding estimates of edge distance versus bird nesting success (e.g., Gates and Gysel1978, Yahner and Wright 1985, Angelstam 1986, Ratti and Reese 1988, Small and Hunter 1988, Temple and Cary 1988,Averyetal. 1989,Yahner 1991, and Paton 1994). Robinson et al. (1995) explain that in more fragmented landscapes, cowbirds may saturate breeding habitats resulting in nest parasitism > 600 m from forest edges. However, less fragmented forested landscapes that have fewer agricultural areas, i.e., fewer cowbird foraging sites, have shown reduced parasitism within the forest (Robinson et al. 1995). Both types of fragmentation are found in Indiana. For instance the northem half of the state is relatively flat with predominantly agricultural land use and small forest patches. In contrast, the largest forest areas are located in south-central Indiana where elevation is much more variable. The smaller forest patches in the north had higher edge/area ratios, making them potentially more susceptible to cowbird nest parasitism. The reverse is true for the larger less fragmented forests of south- central Indiana.

In our analysis, forest core areas ≥ 600 m from an edge represent only 13% of the forest land; the majority of these interior areas are located in and around Brown County in south-central Indiana (Figure 4; red areas). Public lands containing some of these core areas include Brown County State Park, Yellowood State Forest, Morgan-Monroe State Forest, Owen-Putnam State Forest, and Hoosier National Forest. In contrast, northern Indiana is highly fragmented with relatively little core area > 600 m from an edge. Using a stochastic computer model, Temple and Cary (1988) found dramatic differences in mean population sizes of forest-interior birds between landscapes that are fragmented (similar to northern Indiana) and unfragmented (similar to portions of south central Indiana).

Riparian Corridors

In this study we modeled reforestation only in riparian zones that were not already forested. However, some of these nonforest areas could have had other types of native vegetation in them such as grass. We would have preferred to leave this native vegetation as part of the buffer and to have modeled reforestation only in areas that did not contain native vegetation. However, native vegetation types other than forest were not shown as such in our GIS data and therefore would have been planted as forest in our riparian zone model. When more detailed vegetation cover data become available, models that consider existing native vegetation other than forests can be developed. Also, in future models some riparian zones might be planted with native vegetation such as prairie species, particularly in northwestern Indiana.

Fragmentation of forests of all ages would be considerably reduced if nonforest riparian zones were restored to forest. This would connect over 5,874 forest fragments. Because the resolution of our data was 200 x 200 m, the vegetation buffer was 200 m wide (and represents a simplified model). It is not likely that both sides of a stream or river would be reforested at this width. More acceptable buffer widths might be in the range of 20 to 50 m. A 20-m buffer would require approximately 90%

less area and a 50-m buffer would require approximately 75% less area than the 200-m buffer used in this model. With finer resolution data we could apply wide buffers to rivers, narrow buffers on streams, and a range of widths for waterways of varying intermediate sizes. But corridor width may not be as important as corridor presence for some species. For instance Polla and Barrett (1993) found that corridor (buffer) width was less important than corridor presence in influencing corridor use by the meadow vole (*Microtus pennsylvunicus).* However, successional stage, presence of physical barriers, and extent of human use also may influence corridor use by vertebrates.

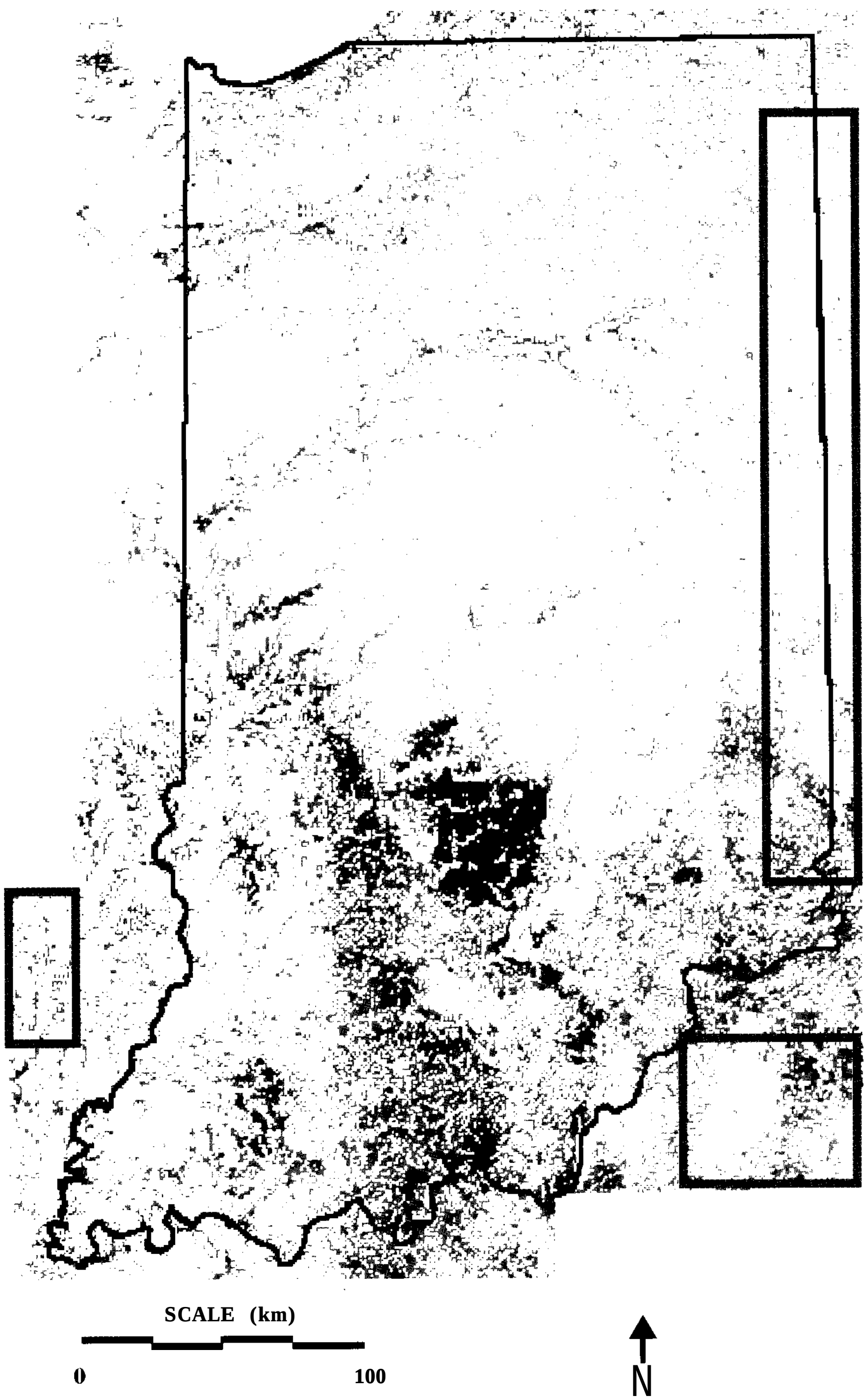

Figure 4. Map of all forests in Indiana and surrounding areas. Red areas show forest core areas ≥ 600 m from a forest/nonforest edge and represent 13% of the forest. Most of Indiana and the surrounding area consists of unconnected forest patches in an agricultural matrix. Only the south central portion of the state has forests that are very contiguous and large (Figure 2). Therefore, this Is where most core areas ≥ 600 m from a forest/nonforest edge exist. We used all forest cover data available to us at a 200-m resolution to construct these maps. The rectangles show the three areas for which there were no riparian data. There were a total of 972 forest patches in these three areas—the eastern edge of Indiana, one in Kentucky, and one area in Illinois. The riparian corridor model included all but these three areas.

Recommendations for managers

When possible, riparian corridors should be restored to forest. Potential advantages of such corridors include an increased ability for species to adjust to long-term climate changes, greater movement of organisms, soil stabilization, and an increased level of water quality. Hunter et al. (1988) suggested that large-scale corridors would allow species to adjust their distributions as climate changes. They also suggested that corridors allow organisms to move more freely among reserves, supporting gene flow and reducing local extinction.

Henderson et al. (1985) found that fencerow corridors were critical to the movement of chipmunks among forested patches in an agricultural mosaic. Forested riparian zones may provide dispersal routes while providing food, water, and cover (Thomas et al. 1979). In addition, vegetation along riparian areas stabilizes soil and provides necessary inputs of organic matter (Jahn 1978). The results of a 5-year study found that logs that fell across streams dissipate flow energy, maintain channel stability, decrease bedload movement, and increase water quality (Heed 1985). Small streams frequently receive runoff directly from agricultural operations, showing higher peak agricultural chemical concentrations than larger rivers (Baker and Richards 1989).

Isolation of Old-Growth Forests

As there are no known species obligately restricted to midwestem old-growth forest remnants, isolation could be considered an advantage. The scattering of sites reduces the probability that any one natural catastrophe could affect more than one site.

However, edge metrics for the 19 old-growth sites show the advantage they gain from being part of a forested landscape (Table 3). The mean values for percent edge in the 40-m, 200-m, 400-m. and 600-m widths of edge were lower when the 19 sites were considered in the all forests landscape than when considered as isolated old growth. Eleven are surrounded by forests in private ownership. According to the Indiana Department of Natural Resources Division of Forestry, the average privately owned forest changes ownership approximately every 15 years. As ownership changes so do the ownership objectives. Therefore, it is not certain whether forests adjacent to areas containing these 11 old-growth sites will remain intact. The other 8 sites are adjacent to or surrounded by publicly owned forest. Scout Ridge Nature Preserve and Laughery Bluff Nature Preserve are the only sites completely surrounded by other forest. Both sites have been damaged by straight line winds—Scout Ridge in 1989 and Laughery Bluff on June 4, 1993. If allowed to develop old-growth characteristics, a portion of the surrounding forests could provide old-growth structure lost during the storms.

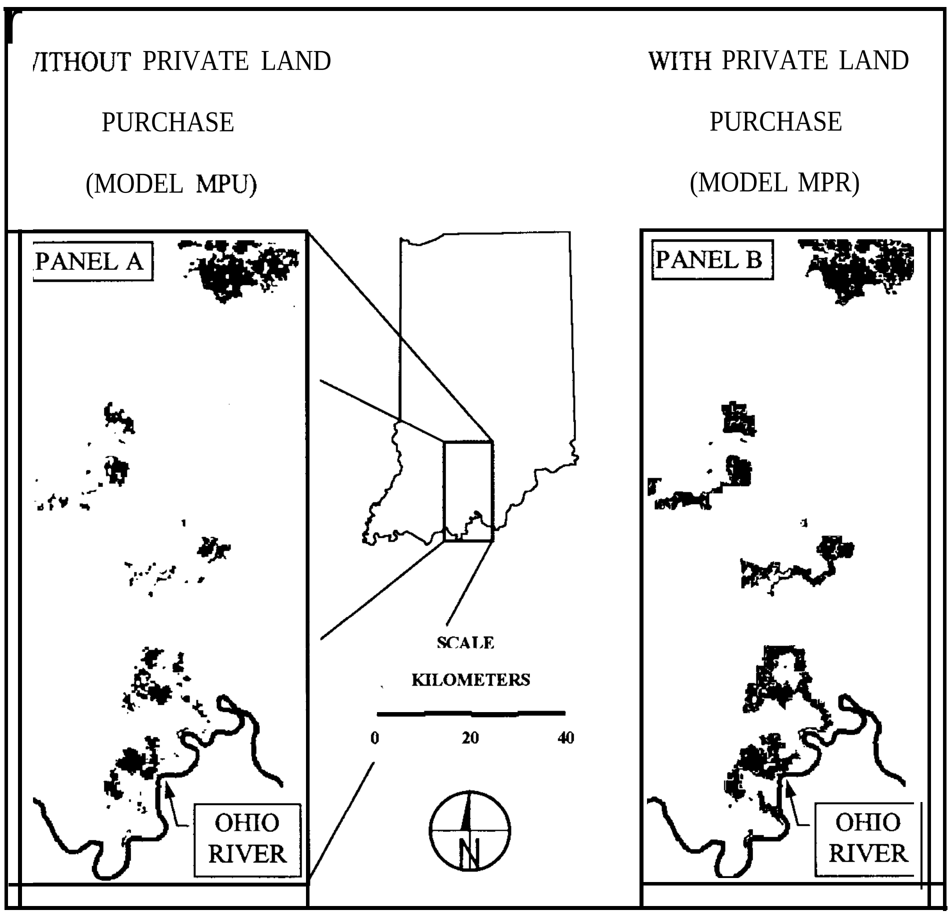

Figure 5. Hoosier National Forest (HNF). The 98 sites In panel A are areas currently In HNF ownership that have been set aside to develop old-growth characteristics (model MPU, HNF only). The 19 sites In panel B include private lands that are within HNF purchase boundaries (model MPR, HNF only). The 19 larger consolidated sites result In a smaller PX value In MPR because of greater distance between sites (greater than 600 m In most cases). PX values of forest patches In the southern three-fourths of the area In panel A range up to 16 to 32 compared with ≤ 0.5 In panel B. However, there Is little change In the PX value of the northern 1/4 of thls scene.

Recommendations for managers

Our first recommendation is to reduce edge through tree planting or by allowing natural succession to take place. The advantages of a surrounding younger forest should be considered in future land acquisitions of public land-holding agencies. Harris (1984) discussed these advantages in detail for western forests. In a similar design, Mladenoff et al. (1994) suggest designated buffer zones surround old-growth sites. Harvest intensity within the buffer would be lower the closer the buffer is to the old-growth site. In this design, there would be no harvesting in the 100-m zone closest to the old-growth site. Some advantages for midwestem forests would be increased biotic diversity; reduced edge effects such as wind, solar radiation fluxes, and reduced human disturbance; and alternate forests to take over when wind damage or other catastrophic events take place. Younger forests are generally less damaged by wind because there are more flexible stems and less internal decay in younger trees.

Old-Growth Forest Combined with Potential Old-Growth Forest

Although there was no increase in PX of the 19 old-growth forest remnants after adding them to the potential old-growth landscape, there were other advantages to adding the potential sites. The major change resulting from the addition of potential old-growth sites was an increase in the number of hectares. In addition, connectivity is greater for all potential old-growth sites compared to the 19 present-day old-growth sites. However, empirical studies relating PX to organism movement have not been conducted. Until such studies are complete, PX values are best used as an indicator of patch density and accessibility in fragmented landscapes (Gustafson and Parker 1994). Based on model MPU, which considered only publicly owned lands, the area of old-growth forest would increase from 362 ha to 55,223 ha, and the average PX value would increase from 0, for the 19 sites existing now, to 3.9 among 216 sites. For MPR, which includes all of the above sites plus areas within the HNF purchase bound-

Table 3. Percent of total area of Indiana old-growth sites in edge for four theoretical edge widths. "Old-Growth Landscape" is simply the 19 old-growth sites without any other forest in that landscape. See Table 2 for full site names.

		Percent Area in Edge-Old-Growth Landscape				Percent Area in Edge—All Forests Landscape			
Old-Growth Site	Size (ha)	40 m	200 m	400 m	600 m	40 m	200 m	400 m	600 m
Bendix Woods	10.9	49	loo	loo	loo	4	37	65	91
Eunice H. Bryan	11.7	44	loo	loo	loo	41	loo	loo	loo
Calvert And Porter Woods	16.2	34	100	100	100	28	100	100	100
Davis-Purdue	20.6	32	100	100	100	22	100	100	100
Donaldson Woods	27.1	32	100	100	100	4	37	72	100
Hemmer Woods	26.3	42	100	100	100	38	100	100	100
Hoot Woods	33.2	30	100	100	100	12	64	100	100
Kieweg Woods	17.4	36	100	100	100	23	100	100	100
Kingsbury Black Oak Woods	16.2	35	100	100	100	32	100	100	100
Laughery Bluff	15.0	61	100	100	100	0	17	100	100
Lubbe Woods	13.8	45	100	100	100	27	94	100	100
McNabb-Walter	7.7	100	100	100	100	55	100	100	100
Pioneer Mothers	15.0	54	100	100	100	3	20	49	84
Scout Ridge	6.1	56	100	100	100	0	0	0	0
Shrader-Weaver	11.3	42	100	100	100	41	100	100	100
Tribbett Woods	13.4	36	100	100	100	28	100	100	100
Wells Woods	8.1	52	100	100	100	31	100	100	100
Wesselman Woods	76.9	20	72	100	100	14	63	100	100
Woolen's Garden	15.4	59	100	100	100	30	100	100	100
Mean Values	19.1	45	99	100	100	23	75	89	93
Standard Deviation of Poplulation	15.2	17	6	0	0	15	34	25	22

Note: Edge percent for 200,400, and 600 m was determined directly from 7.5-min. quadrangle maps for better accuracy.

aries currently in private ownership, the area of old-growth forest would increase to 82,520 ha with an average PX value of 1.8 among 137 sites. Notice that even though more area is added in the second model, the PX value and number of sites have decreased. Many of the smaller areas have been connected to form several large areas within the HNF, but these large sites are isolated. Although fragmentation at one scale was reduced in this case, PX does not reflect this (Figure 5).

Percent edge area of the potential old-growth sites was less than the percent edge area of the current 19 sites at all four edge widths. The difference in percent edge can be attributed to the potential sites having larger average sizes: 128 ha for publicly owned lands less HNF sites, 256 ha for the publicly owned forest model (MPU), and 602 ha for the model that includes all sites within the HNF purchase boundaries currently in private ownership (MPR). The current 19 sites have an average size of 19.1 ha. There are probably additional potential old-growth sites in state parks that will develop old-growth characteristics. However, the response from the Indiana Division of State Parks indicated that any site not designated as a state nature preserve could potentially be used as a recreational site in the future. Therefore, they could not designate any other areas as future old-growth forest at that time.

Recommendations for managers

Although the addition of future old-growth forest significantly increased total area of these forests, they were still relatively isolated from one another. We recommend connecting future old-growth sites through riparian or other corridors to increase connectivity. Some of these areas could be connected through cooperative agreements with private landowners. For instance in Indiana, landowners receive a reduced tax rate on land that is planted or managed as forest through the Classified Forest program. Similarly the Classified Wildlife program provides a reduced tax rate to landowners who maintain wildlife habitat. Lands in the wildlife program could be planted to nearly any native species.

The Nature Conservancy also provides incentives to landowners to care for their lands. In addition, private land trusts such as the Acres, Inc., and Northern Indiana Citizens Ecosystems Service (NICHES) purchase lands and may be willing to help.

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